

# Discovery of an X-ray pulsar in the low-mass X-ray binary 2A 1822–371

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## ABSTRACT

We report the discovery of 0.59 s X-ray pulsations from the low-mass X-ray binary, 5.57 hr dipping and eclipsing ADC source 2A 1822–371. Pulse arrival time analysis indicates a circular orbit with  $e < 0.03$  (95% confidence) and an  $\text{asini}$  for the neutron star of  $1.006(5)$  lightseconds, implying a mass function of  $(2.03 \pm 0.03) \times 10^{-2} M_{\odot}$ . The barycentric pulse period was  $0.59325(2)$  s in 1996.270 and  $0.59308615(5)$  s in 1998.205, indicating an average spin up with  $\dot{P}/P = (-1.52 \pm 0.02) \times 10^{-4} \text{ yr}^{-1}$ . For a magnetic field strength of  $\sim 1\text{--}5 \times 10^{12}$  G as derived from the X-ray spectrum the implied intrinsic X-ray luminosity is  $\sim 2\text{--}4 \times 10^{37}$  erg s $^{-1}$ . The pulse amplitude is low, but increases steeply as a function of energy from a sinusoidal amplitude of 0.25% in 2–5.4 keV to  $\sim 3\%$  above 20 keV. We discuss the constraints on the masses of the companion star and the fact that several aspects of the energy spectrum are in qualitative accordance with that of a strongly magnetised neutron star.

*Subject headings:* accretion, accretion disks — stars: individual (2A 1822–37) — stars: neutron — stars: binaries: eclipsing — pulsars: individual (2A 1822–37) — X-rays: stars

## 1. Introduction

The lightcurve of the low-mass X-ray binary (LMXB) 2A 1822–371 shows clear signs of orbital modulation in both the X-ray and optical bands (White et al. 1981; Seitzer et al. 1979; Mason et al. 1980), with a period of 5.57 hours. White et al. (1981) showed that the X-rays are emitted from an extended source, a so called Accretion Disk Corona (ADC) which is periodically partially eclipsed by the companion star (at orbital phase 0.0) as well as partially obscured by structure in the accretion disk whose height above the orbital plane varies but is greatest at phase 0.8 and least at phase 0.2 (White et al. 1981). The implied inclination is  $i > 70^\circ$  (Mason et al. 1980). The short orbital period makes 2A 1822–371 a compact LMXB. If powered by a Roche lobe filling main-sequence star the companion mass is  $0.62 M_{\odot}$ , however, the companion spectrum is inconsistent with that of a normal K-star (Harlaftis et al. 1997).

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The orbital period has been measured from eclipse timing to gradually increase (Hellier et al. 1990); the best ephemeris to date was provided by Parmar et al. (2001). The observed X-ray spectrum is complex and various models have been used to describe the data. With a power law index of  $\sim 1$  (Parmar et al. 2001) the continuum is harder than that of typical LMXBs which have power law indices of 1.5–2.5. There is also evidence for a strong soft component in the 1–10 keV range (e.g. Heinz & Nowak 2001; Parmar et al. 2001). An upper limit on the presence of pulsations in the 1–30 keV band of 1% was derived by Hellier et al. (1992).

Soon after the discovery of accreting X-ray pulsars (Giacconi et al. 1971) it was realized that these are strongly magnetized ( $B > 10^{12}$  G) neutron stars accreting matter from an accretion disk (Pringle & Rees 1972; Lamb et al. 1973) or a stellar wind (Davidson & Ostriker 1973). Whereas accretion-powered pulsars are common in massive X-ray binaries, they are rare in LMXBs, a fact that has been explained in terms of neutron star magnetic field decay (presumably accretion-induced) in the generally much longer-lived low-mass systems (Bhattacharya & Srinivasan 1995). The lower field would allow the disk to extend to close to the neutron star and spin it up to millisecond periods. This is in accordance with binary evolutionary models predicting that LMXBs are the progenitors of binary millisecond radio pulsars (Radhakrishnan & Srinivasan 1982; Alpar et al. 1982; see for a detailed description Bhattacharya 1995). This scenario was confirmed by the discovery of the first accreting millisecond pulsar, in the LMXB SAX J1808.4–3658 (Wijnands & van der Klis 1998). In this Letter, we report the discovery of pulsations in the LMXB 2A 1822–371, and describe our measurements of both the orbital Doppler shifts and the spin-up of the pulsar. We briefly discuss the constraints on the masses of the two binary components and also the energy spectrum of the pulsar.

## 2. Observations and analysis

We used 16 observations obtained on 1996 Sept. 26 and 27 (observations 1–5), 1998 June 28 and 29 (observations 6–11), and July 24 and 25 (observations 12–16) with the proportional counter array (PCA; Jahoda et al. 1996) onboard the *Rossi X-ray Timing Explorer* (RXTE) satellite (Bradt et al. 1993). The total amount of good data was  $\sim 73$  ksec. All observations yielded data with a time resolution of at least  $2^{-13}$  s, in 64 energy bands covering the effective 2.0–60 keV energy range of RXTE.

As part of a systematic search for pulsars in LMXBs (Jonker et al. in prep.), a power spectrum of Solar System barycentered data was created using an FFT technique. The Nyquist frequency was 64 Hz. A weak 0.59 s pulsed signal was discovered first in the 2.0–60 keV power spectrum. Investigation of the pulsed signal in various energy bands and different sub-sets of the data showed that the signal-to-noise ratio was highest in the 9.4–22.7 keV band of observations 12–16. Therefore, we initially used this energy band and subset of the data for our analyses.

We measured the Solar System barycentric pulse period in 19 data segments of observations 12–16

each with a length of  $\sim 1500$  s (half a typical RXTE contiguous data segment) using an epoch folding technique. The period of the pulsar showed clear evidence of the 5.57 hour orbital modulation due to orbital Doppler shifts with an amplitude corresponding to an  $a\sin i$  of about 1 light second. Correcting for the orbital delays using the previously known orbital ephemeris (Parmar et al. 2001) and our best measure of  $a\sin i$  obtained from the pulse period analysis, we epoch-folded each 1500 s segment in observations 12–16, and measured the phase of each folded profile by fitting it with a sinusoid. The residual phases were then fitted with a model using a constant pulse period and a circular orbit. This satisfactorily described the observed dependencies on both time and orbital phase. The best-fit orbital and pulse parameters are given in Table 1. The measured pulse arrival times and the best-fit orbital delay curve are displayed in Fig. 1.

Assuming our measured  $a\sin i$  and the orbital ephemeris of Parmar et al. (2001) we found for observations 1–5 a pulse period of  $0.59325(5)$  s. This is significantly longer than that during observations 12–16 (see Table 1), a conclusion that is insensitive to the details of the orbital corrections. From this difference we derived a pulse period derivative of  $\dot{P} = (-2.85 \pm 0.04) \times 10^{-12} \text{ ss}^{-1}$ . Due to the weakness of the signal and the limited amounts of data we were not able to phase-connect the data within observations 1–5 or 6–11, nor could we maintain the pulse count between the epochs of observations 1–5, 6–11, or 12–16.

Using the parameters in Table 1 we folded 30 ksec of data of observations 12–16 in the energy bands 2.0–5.4–9.4–13.8–22.7–60 keV to measure the pulse shape and the pulse amplitude as a function of energy. The pulse profiles are consistent with being the same in each energy band and did not change significantly as a function of binary phase. The best pulse profile was obtained combining the energy bands 9.4–13.8 keV and 13.8–22.7 keV (see Fig. 2). We fitted a single sinusoid to the profile in each energy band to measure the amplitude. The pulse amplitude depends strongly on energy, increasing from  $0.25\% \pm 0.06\%$  in the 2.0–5.4 keV band to  $2.8\% \pm 0.5\%$  in the 22.7–60 keV band (Fig. 3). The pulse amplitude was lower in observations 1–5 than in observations 6–11 and 12–16 ( $\sim 1.2\%$  versus  $\sim 1.7\%$  and  $\sim 2.1\%$  in the 13.8–22.7 keV band, respectively). Although a single sinusoid is not a perfect representation of the pulse profile this will not significantly affect the derived pulse phase differences or pulse amplitude spectrum, as the profile is constant within the errors.

### 3. Discussion

Using data obtained with the RXTE satellite we have discovered 0.59 s X-ray pulsations from the low-mass X-ray binary (LMXB) 2A 1822–371 with  $\dot{P}/P = -1.5 \times 10^{-4} \text{ yr}^{-1}$ . This is the sixth LMXB to show pulsations (Table 2), the fourth whose orbital pulse delay curve was measured, and after SAX J1808.4–3658 only the second compact LMXB ( $P_{\text{orb}} < 12$  hrs) for which this was done. Contrary to SAX J1808.4–3658, 2A 1822–371 is optically bright and has a well-constrained inclination (because it is eclipsing), which might allow for a future full binary solution. Before our measurements, the nature of the compact object in 2A 1822–371 was somewhat uncertain. Heinz

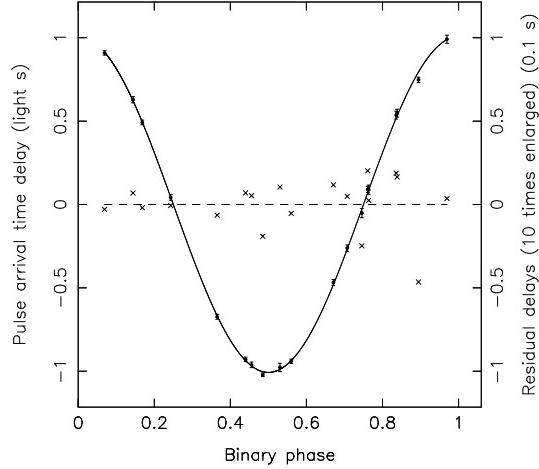


Fig. 1.— The arrival time delay in light seconds of the pulses due to the orbital motion of the neutron star as a function of binary phase. Phase zero is superior conjunction. Each dot represents  $\sim 1500$  s of data obtained in observations 12–16. The sinusoid is the best fit to the dots. The residuals of the fit (crosses) are shown at a 10 times expanded scale. Error bars are shown for the dots; for clarity they are omitted for the residuals.

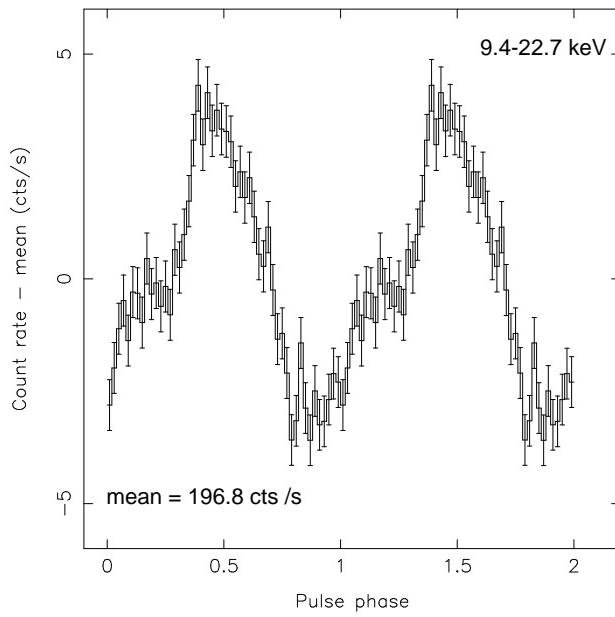


Fig. 2.— The measured pulse profile obtained from epoch folding the 9.4–22.7 keV data of observations 12–16. The mean count rate (indicated) was subtracted. For clarity two periods are plotted. The profile is clearly non-sinusoidal. Phase zero is at HJD 2451019.4011752. The bin size is  $\sim 0.01$  s. One sigma error bars are shown.

& Nowak (2001) showed that it could either be a white dwarf, a neutron star or a low-mass black hole. Our detection of pulsations, together with spin period changes on a timescale of  $\sim 10^4$  years establishes that the compact object is a neutron star. We derive a mass function for the companion star of  $(2.03 \pm 0.03) \times 10^{-2} M_\odot$ . This, combined with the knowledge of the inclination constrains the masses of the two components to a small area in a plot of companion star mass versus neutron star mass (the shaded region in Fig. 4). If the companion is a main sequence Roche-lobe filling star subject to the usual lower main sequence mass-radius relation (Kippenhahn & Wiegert 1990) its mass is  $0.62 M_\odot$  (the horizontal line in Fig. 4). This would imply a quite massive neutron star. Spectroscopic observations provide a lower limit to the semi-amplitude of the radial velocity of the companion star (Harlaftis et al. 1997). From that lower limit we constrain the mass of the neutron star to be more than  $0.6_{-0.3}^{+1.0} M_\odot$  (the vertical line in Fig. 4 at  $0.3 M_\odot$  represents the 67% confidence limit). Furthermore, they showed that the inner face of the companion star is 10 000–15 000 K hotter than its back face. This is probably due to effects of X-ray heating, which could render the companion significantly undermassive for its size. For a  $1.4 M_\odot$  neutron star the companion has a mass of  $0.4\text{--}0.45 M_\odot$  (see Fig. 4).

An estimate of the strength of the magnetic field depends among other things on the source luminosity. The luminosity of 2A 1822–371 was estimated (Mason & Cordova 1982) to be  $L_X \sim 1.1 \times 10^{35} \text{ erg s}^{-1}$  ( $d/1\text{kpc}$ ) $^2$ . For a distance of 2.5 kpc (Mason & Cordova 1982) this would lead to  $\sim 10^{36} \text{ erg/s}$ . However, since all observed X-rays are thought to have been scattered by an ADC (see Section 1), the true source luminosity may be as high as  $\sim 10^{38} \text{ erg/s}$  (White & Holt 1982). Such a high luminosity would be consistent with the observed binary orbital period change (Heinz & Nowak 2001). From the luminosity and the spin-up rate the magnetic field can be determined (cf. Ghosh & Lamb 1979); for  $L_X \sim 10^{38} \text{ erg s}^{-1}$  we derive a magnetic field strength,  $B$ , of  $\sim 8 \times 10^{10} \text{ G}$ , whereas for  $L_X \sim 10^{36} \text{ erg s}^{-1}$   $B \sim 8 \times 10^{16} \text{ G}$ , which implies that the luminosity is probably not that low. If we assume that the neutron star is spinning at its equilibrium period, then for  $L_X \sim 10^{36} \text{ erg s}^{-1}$  we find  $B \sim 5 \times 10^{10} \text{ G}$  and for  $L_X \sim 10^{38} \text{ erg s}^{-1}$   $B \sim 5 \times 10^{11} \text{ G}$ . In all this we assumed  $M_{ns} = 1.4 M_\odot$ ,  $I = 10^{45} \text{ g cm}^2$ , and  $R = 10^6 \text{ cm}$  for the mass, moment of inertia, and radius of the neutron star.

The X-ray spectrum of 2A 1822–371 was studied by various authors (White et al. 1981; Hellier & Mason 1989; Hellier et al. 1992; Heinz & Nowak 2001; Parmar et al. 2001; Iaria et al. 2001), using data obtained with different satellites (*Einstein*, *EXOSAT*, *Ginga*, *ASCA*, *RXTE*, and *BeppoSax*). Parmar et al. (2001) discussed several unusual features of the spectrum of 2A 1822–371 and although Compton scattering in the ADC probably also affected the spectrum (White & Holt 1982), in principle some of these features could be explained by the presence of a  $\sim 10^{12} \text{ G}$  pulsar instead of  $10^8\text{--}10^9 \text{ G}$  neutron star. With a power law index of  $\sim 1$  the continuum spectrum is much harder than that of LMXBs of similar luminosity (Parmar et al. 2001). This is, however, a common power law index for X-ray pulsars (White et al. 1983). The observed cut-off at  $\sim 17 \text{ keV}$  (Parmar et al. 2001) could also be explained by the presence of the pulsar. The cut-off energy of pulsars is thought to be approximately half the cyclotron energy (Makishima & Mihara 1992; see White

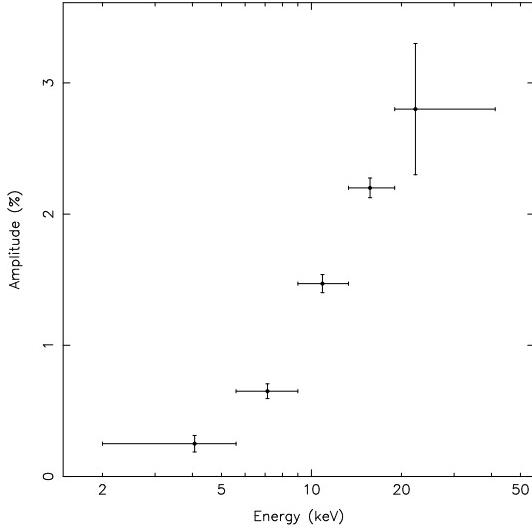


Fig. 3.— Pulse amplitude as a function of energy. The horizontal bars denote the width of the energy bands, while the vertical bars denote  $1\sigma$  uncertainties. The x-coordinate of the dots is the weighted mean photon energy in each band. The pulse amplitude increases steeply with energy.

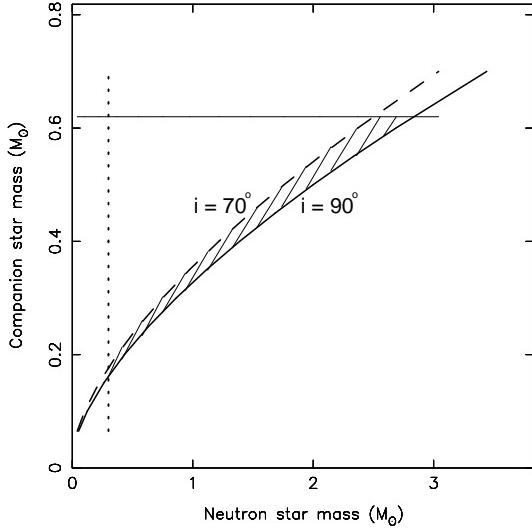


Fig. 4.— Companion star mass as a function of neutron star mass. The system is located between the two curves representing  $i = 70^\circ$  and  $i = 90^\circ$ . The region to the left of the dotted line is excluded (67% confidence) due to the lower limit on the radial velocity of the companion star (Harlaftis et al. 1997). The horizontal line is the mass of the companion assuming it is a Roche-lobe filling main sequence star. The allowed region (shaded) assumes that the companion could be undermassive, not more massive than this.

et al. 1995 for a overview). The strength of the B-field which can thus be derived from the cut-off, assuming a redshift at the neutron star surface of 0.3, is  $\sim 4 \times 10^{12}$  G. The relation between the electron temperature and the energy of the cyclotron resonance (Makishima et al. 1999), leads for a  $kT_e$  of  $\sim 4\text{--}10$  keV (Parmar et al. 2001; Iaria et al. 2001, although fit with a slightly different continuum function than Makishima et al. 1999) to magnetic field estimates of  $\sim 1\text{--}5 \times 10^{12}$  G, again assuming a redshift at the neutron star surface of 0.3. These estimates of the magnetic field are consistent with the estimates derived from the spin-up above. The intrinsic source luminosity would be  $\sim 2\text{--}4 \times 10^{37}$  erg s $^{-1}$  given the  $\dot{P}/P$  we measured.

The neutron star was found to spin up on a timescale of  $\sim 6500$  years;  $\dot{\nu}$  is  $(8.1 \pm 0.1) \times 10^{-12}$  Hz s $^{-1}$ . Comparing this  $\dot{\nu}$  with that in the other LMXB X-ray pulsars (Table 2) we note that the spin-up rate measured over  $\sim 666$  days is large for an LMXB X-ray pulsar, but that of the transient system GRO J1744–28 is even larger (Finger et al. 1996). Recent observational evidence summarized by Bildsten et al. (1997) reveals alternating episodes of spin-up and spin-down in disk-fed neutron stars. If the  $\dot{\nu}$  we measured of 2A 1822–371 between 1996.270 and 1998.205 would be the average of multiple spin-up and spin-down episodes, then the maximum spin-up rate would be even higher. However, episodes of steady spin-up or spin-down lasting nearly a decade have been observed in GX 1+4 and 4U 1626–67 (Chakrabarty et al. 1997a; Chakrabarty et al. 1997b).

The increase in pulse amplitude with photon energy is steeper than has been found for other low-mass X-ray pulsars (4U 1626–67, Rappaport et al. 1977; Her X-1, White et al. 1983; SAX J1808.4–3658, Wijnands & van der Klis 1998). Furthermore, the pulse amplitude is low compared with other LMXB X-ray pulsars. Previous studies revealed that in 2A 1822–371 scattering is important (White et al. 1981; Hellier & Mason 1989; Hellier et al. 1992; Parmar et al. 2001; Heinz & Nowak 2001). Multiple scatterings of the pulsed emission in an ADC of  $0.3R_\odot$  (White et al. 1981) would have washed out the pulse due to light travel time delays. Therefore, at least a portion of the ADC should not be very optically thick. Compton scattering in such an ADC could explain the observed pulse amplitude spectrum.

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Table 1. Orbital parameters of 2A 1822–371. The number in brackets indicates the  $1\sigma$  uncertainty in the last digit.

Barycentric pulse period (s) at 1998.205, $P_{1998}$	0.59308615(5)
Projected semimajor axis (light sec.), $a \sin i$	1.006(5)
Orbital period (s), $P_{\text{orb}}$	20054.240(6) <sup>a</sup>
Epoch of superior conjunction (HJD), T	2450993.27968(2)
Eccentricity, $e$ (95% confidence)	$< 3.1 \times 10^{-2}$
Mass function, $f_x(M_{\odot})$	$(2.03 \pm 0.03) \times 10^{-2}$
Barycentric pulse period (s) at 1996.270, $P_{1996}$	0.59325(2)
Pulse period derivative (s/s), $\dot{P}$	$(-2.85 \pm 0.04) \times 10^{-12}$

<sup>a</sup>From orbital ephemeris of Parmar et al. (2001)

Table 2. Comparing the X-ray pulsars in LMXBs.

Source	$P_{Pulse}$ (s)	$\dot{\nu}$ (Hz/s)	$P_{orb}$ (days)	$a \sin i$	References
SAX J1808.4–3658	0.00249	$< 7 \times 10^{-13}$	0.0839	0.062809(1)	1,2
GRO J1744–28	0.467	$1.2 \times 10^{-11}$	11.8	2.6324(1)	3,4
2A 1822–371	0.5931	$8.1 \times 10^{-12}$	0.232	1.006(5)	5
Her X–1	1.24	$5 \times 10^{-13}$	1.70	13.1853(2)	4,6
4U 1626–67	7.66	$8 \times 10^{-13}$	0.0289	...	4,7
GX 1+4	120	$6 \times 10^{-12}$	~304	...	4,8,9,10

<sup>1</sup>Wijnands & van der Klis 1998<sup>2</sup>Chakrabarty & Morgan 1998<sup>3</sup>Finger et al. 1996<sup>4</sup>Bildsten et al. 1997<sup>5</sup>this paper<sup>6</sup>Tananbaum et al. 1972<sup>7</sup>Rappaport et al. 1977<sup>8</sup>Lewin et al. 1971<sup>9</sup>Chakrabarty et al. 1997a<sup>10</sup>Pereira et al. 1999